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ADHESION CHARACTERISTICS OF
TITANIUM-ALUMINUM ALLOYS IN VACUUM

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SUMMARY

Friction, wear, and adhesion measurements were made in vacuum (10^{-9} mm Hg) of titanium-aluminum alloys containing 11, 16, and 21 weight percent aluminum. Experiments were conducted with a $\frac{3}{16}$ -inch-radius rider sliding on the flat surface of a $2\frac{1}{2}$ -inch-diameter disk specimen at loads to 1500 grams. The disk was rotated to produce sliding velocities to 750 centimeters per second.

With increasing addition of aluminum to titanium, an increase in lattice ratio (c/a) for titanium occurred along with a decrease in friction, wear, and adhesion. The increase in (c/a) lattice ratio with the addition of aluminum to titanium occurred even though the unit cell size decreased; these results are unlike those with the addition of tin and oxygen to titanium. While titanium exhibited an adhesion coefficient of 5.3, the titanium-aluminum alloys exhibited adhesion characteristics which could be considered negligible.

These alloys exhibited superior friction and wear properties in vacuum compared with 52100 and 440-C stainless steels. Experiments were conducted with the alloys sliding on themselves and on 440-C stainless steel. Friction was less for the alloys sliding on 440-C stainless than when sliding on themselves.

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INTRODUCTION

Marked differences in adhesion, friction, wear, and welding tendencies are found for metals with different crystal structures (refs. 1 to 5). Those metals possessing hexagonal crystal structures or polymorphic metals in the hexagonal form exhibit lower friction, wear, and adhesion characteristics than cubic metals or polymorphic metals in the cubic form. Further, with the hexagonal metals which exhibit the lower friction and wear characteristics, a dependence upon lattice parameters is found (ref. 5). Those hexagonal

metals possessing near ideal slip behavior (basal slip) have lower friction characteristics than those exhibiting prismatic and pyramidal slip (Ti, Zr, and Hf) (ref. 5).

With metals such as titanium, the addition of alloying elements which expand the crystal lattice in the C-axis direction (increased c/a ratio) results in a decrease in friction coefficient. Elements such as tin and oxygen have this effect upon titanium; they increase the c/a lattice ratio by increasing the C-axis (ref. 6).

There are, however, elements which increase the c/a lattice ratio even though the individual lattice parameters (c and a) decrease with increasing amount of alloying element. That is, the unit hexagonal cell is decreasing in size but the rates of decrease of c and a with addition of alloying element are such that the ratio c/a increases. An example of such an alloy system is aluminum in titanium.

If the significant parameter is lattice ratio c/a , the addition of aluminum to titanium should do more to reduce friction, wear, and welding tendencies of titanium than tin and oxygen. With decreasing unit cell size, an increase in atomic packing density will occur. The influence of atomic density on friction at this time is not known. An attractive feature of aluminum as an alloying element with titanium is that the alloy itself would have low density. (Light weight is an important consideration in aerospace devices.)

shot [This investigation was conducted to determine in a vacuum environment whether the lattice ratio c/a or the interatomic distance along the C-axis in the hexagonal metal titanium is of primary importance in determining the friction characteristics of titanium. Crystallographic considerations would indicate that the ratio c/a is the important parameter since slip mechanisms in hexagonal crystals depend upon it. The experiments of this study were conducted with aluminum alloyed in titanium. Since aluminum increases the c/a ratio of titanium with a decrease in unit cell size and data exist for systems which expand the C-axis (titanium-oxygen and titanium-tin), the factor responsible for a decrease in friction characteristics with such alloy additions can be resolved.] *app 3*

The experiments of this investigation were conducted with a hemispherical rider specimen sliding on a flat disk surface. All experiments were made at a pressure of 10^{-9} millimeter of mercury or lower to reduce the presence of surface contaminants. Friction, wear, and adhesion measurements were made with titanium as well as with titanium-aluminum alloys. Adhesion measurements were made with copper for reference purposes.

ALLOY PREPARATION

The titanium-aluminum alloys used in this investigation were all arc-cast under argon at reduced pressure. Small pieces of the metals to be cast were placed in a water-cooled copper mold and arc-melted with a tungsten electrode. The casting was then turned over in the mold and remelted. This process was repeated a number of times to ensure homo-

geneity in the casting. After the alloys cooled, they were removed and metallographic and chemical analyses were made. Friction and wear specimens were then prepared. In order to ensure that the structure was primarily hexagonal rather than cubic (alpha rather than beta), all samples were sealed in evacuated tubes and heat-treated at 1400°F (760°C) for 72 hours.

[APPARATUS AND EXPERIMENTAL PROCEDURE]

The apparatus used in this investigation is shown in figure 1. [The basic elements of the apparatus were the test specimens (a $2\frac{1}{2}$ -in. -diam. flat disk and a $\frac{3}{16}$ -in. -rad. rider) mounted in a vacuum chamber.] The disk specimen was driven through a magnetic drive coupling. The coupling consisted of two 20-pole magnets spaced axially 0.150 inch apart with a 0.030-inch diaphragm between magnet faces. The drive magnet outside the vacuum system was coupled to a hydraulic motor. The driver magnet was completely enclosed with a nickel-alloy housing (cutaway in fig. 1) and was mounted at the upper end of the shaft within the chamber. The disk specimen was at the lower end of the shaft.

The rider specimen was supported in the specimen chamber by an arm mounted by gimbals and sealed by a bellows to the chamber. [A linkage at the end of the retaining arm away from the rider specimen was connected to a strain-gage assembly. The assembly was used to measure frictional force. Load was applied through a dead-weight loading system. Directly opposite the load (at 180°) was a strain-gage assembly for measuring adhesion forces.]

Attached to the lower end of the specimen chamber was a 400-liter-per-second ionization pump and a vac-sorption forepump. [The pressure in the chamber adjacent to the specimen was measured with a cold-cathode ionization gage. Also present in the apparatus was a diatron-type mass spectrometer (not shown in fig. 1) for determination of gases present in the vacuum system.] A 20-foot, $5/16$ -inch-diameter stainless-steel coil was used for liquid-nitrogen and liquid-helium cryopumping of the vacuum system.

The vacuum chamber and specimens were baked out at 200°C for 16 hours prior to each experiment. [In the adhesion experiments with copper, the specimen was heated to 400°C with an electron gun to drive off and dissociate surface adsorbates and oxides.]

The adhesion coefficient (ratio of breakaway load to applied load) was determined after the friction studies were completed. The rotating drive was stopped and the specimens were left in contact under load for 90 minutes. Then a small drive motor with a strain-gage assembly (fig. 1) was used to separate the specimens, and the force required was recorded on a strip chart. → p 4

[SPECIMEN FINISHING AND CLEANING PROCEDURE]

[The disk and rider specimens used in the friction and wear experiments were finished to a roughness of 4 to 8 microinches. Before each experiment, the disk and rider were given the same preparatory treatment: (1) a thorough rinsing with acetone to remove oil and grease, (2) a polishing with moist levigated alumina on a soft polishing cloth, and (3) a thorough rinsing with tap water followed by distilled water.] For each experiment, a new set of specimens was used.

RESULTS AND [DISCUSSION]

Crystal Forms of Titanium

Titanium alloys exist in a number of forms. These are alpha-stabilized (hexagonal crystalline form), beta-stabilized (cubic crystalline form), and alpha-beta alloys in which a mixture of the two crystalline forms exist. The cubic form (beta titanium) is often selected for structural uses because of improved strength characteristics. For slider materials use, the chief criterion has been hardness.

[In reference 4 the addition of tin and oxygen (alpha stabilizers) to titanium was found to reduce friction markedly. Both alloying elements expanded the lattice ratio c/a , the factor believed primarily responsible for a reduction in friction. They also, however, at the same time expanded the unit cell by expanding both the c and a lattice dimensions. With the addition of aluminum to titanium, the lattice ratio c/a increased but the unit cell dimensions decreased as shown in figure 2 (from ref. 6). Lattice ratio as well as c and a parameters are also shown for tin additions to titanium. Two effects are to be noted from these data: (1) a reduction in unit cell size of titanium with the addition of aluminum and an expansion in unit cell size with the addition of tin, and (2) a much closer approach to the ideal stacking ratio (and, hence, basal slip) with the addition of aluminum.]

[Alloys with 11, 16, and 21 weight percent aluminum in titanium were prepared.] The 21-weight-percent alloy approaches the maximum solubility of aluminum in titanium. A photomicrograph of the 21-weight-percent alloy as well as unalloyed titanium is shown in figure 3. Note particularly the platelet-like structure within the grains of the alloy (fig. 3(b)). The 11- and 16-weight-percent alloys had structures similar to the 21-weight-percent-alloy, but the platelets were not as pronounced.

[Friction of Titanium and Titanium Alloys] → p 5

The friction coefficients for the three aluminum-containing alloys were measured.

The results obtained are presented in figure 4 together with friction data for the tin-titanium system (ref. 4) and the lattice ratios for both the tin- and aluminum-containing systems. The direct relation between friction and lattice ratio for the two hexagonal alloys systems can be readily seen. As the lattice ratio increases, a reduction in friction occurs.

^{7:55} [The friction and wear characteristics were measured for the titanium-aluminum alloys sliding on themselves and on 440-C stainless steel. The results obtained in these experiments together with data for 99.99-percent titanium are presented in figure 5.]

[With the titanium-aluminum alloys sliding on themselves, higher friction but lower wear was observed than for these alloys sliding on 440-C stainless steel.] The increased friction for the alloys sliding on themselves is believed to have resulted from severe plastic deformation of the disk specimen and a plowing contribution to friction. [With titanium sliding on titanium, severe adhesion and metal transfer was noted. With the alloys, the wear track on the disk surface was very smooth with periodic "built-up" and depressed areas indicating plastic flow. With the alloys sliding on the 440-C disk surface, a thin film of the aluminum-titanium alloy was transferred to the 440-C surface. With the aluminum-titanium alloys sliding on themselves, much of the interfacial energy produces plastic flow in the disk of the same hardness; with the harder 440-C disk (nearly twice the alloy hardness), shear of the binary rider alloy occurs.]

Photomicrographs of the rider and the disk of the titanium - 21-weight-percent aluminum are presented in figure 6 with a surface profile of the disk wear area. Figure 7 contains surface profile traces of disk wear areas and photomicrographs of these areas for 99.99 percent titanium and titanium - 11-weight-percent aluminum alloy. As is evident from figure 7, considerable metal transfer to the titanium disk surface occurred. This transfer was not observed, as mentioned earlier, for the aluminum-containing alloys sliding on themselves.

[The influence of sliding velocity upon friction for the titanium - 21-weight-percent-aluminum alloy sliding on 440-C stainless steel is shown in figure 8. From figure 8 it is apparent that in vacuum in the limits of this investigation, sliding velocity (interface temperature) has very little effect on friction coefficient for the alloy. Data for 99.99-percent titanium are included for reference purposes. Unlike the alloy, the friction characteristics for titanium seem to be sensitive to sliding velocity (and lower interface temperature).]

[The possible influence on plastic flow, or plowing, of the titanium-aluminum alloys was mentioned earlier. In order to gain further evidence for this occurrence, friction experiments were conducted at various loads to 1500 grams (fig. 9). At loads of 750 grams, the friction coefficient was load dependent. Beyond 750 grams, the friction coefficient was essentially load independent. The results of figures 8 and 9 seem to substantiate the plastic flow of the titanium-aluminum disk specimens. If the load addition were a simple

→ p 6

surface temperature effect, friction coefficient should change with speed as well as load. This change, however, was not observed.]

The titanium alloys containing various percentages of aluminum had a maximum hardness of Rockwell C-30. The additions of small amounts of oxygen to titanium markedly increase its hardness. If the oxygen concentration exceeds 0.5 percent, however, embrittlement of the titanium occurs. A titanium - 21-weight-percent-aluminum alloy that contained 0.35 percent by weight oxygen was therefore prepared. The alloy hardness increased to Rockwell C-38. Friction experiments were then conducted with the alloy sliding on itself and on 440-C stainless steel. The results obtained together with those for the alloys without the oxygen are presented in figure 10. The presence of oxygen in the alloy did very little to reduce the coefficient of friction for the titanium-aluminum alloy.

Friction data for titanium, aluminum, and the binary alloys of these two elements sliding on 440-C are also presented in figure 10. The marked effect of alloying the two elements on friction can be readily seen.

A comparison of the friction and wear characteristics of the titanium - 21-weight-percent aluminum alloys with the characteristics of conventional bearing steels in vacuum is shown in figure 11. Both friction and wear for the simple binary titanium-aluminum alloys were less than those obtained with 52100 or 440-C stainless steel sliding on themselves in vacuum. When the binary alloys slid on 440-C rather than on themselves, some increase in wear rate over that for 52100 was noted. It should be pointed out, however, that 52100 welded completely in vacuum and made the value of wear difficult to interpret.

[Adhesion of Titanium-Aluminum Alloys]

[The adhesion characteristics of the titanium-aluminum alloys were determined after each experiment. (Preliminary experiments were conducted with copper for reference purposes.) The adhesion coefficient (ratio of breakaway force to applied load) was measured under four conditions: (1) with the specimens in normal contact, (2) with residual surface oxides present, (3) with the surface cleaned to remove these oxides, and (4) with the specimens in sliding contact prior to adhesion measurements. The specimens were rotated, because, for materials in sliding contact, either work hardening or increased contact area can occur as a result of severe plastic deformation.] The influence of these effects upon adhesion has been noted elsewhere (ref. 3). The greater the work hardening, the greater the adhesion; and the larger the contact area, the greater the force required to separate two surfaces.

The adhesion characteristics of titanium and titanium-aluminum alloys were measured after rotation of the specimens. The 99.99-percent-titanium experiment had to be terminated after 30 minutes because of severe welding. [The measured coefficient of

adhesion was 5.3 (see table I). [With the titanium-aluminum alloys, the specimens did not show measurable adhesion after rotation of 1 hour.] Titanium cannot be grouped with hexagonal metals exhibiting the basal slip mechanism (zinc, cadmium, etc.). Titanium normally exhibits prismatic and pyramidal slip. As a consequence, it may behave quite differently under deformation; that is, its behavior may be more characteristic of cubic than of hexagonal metal.

When an alloying element is substituted within the lattice structure of titanium in order to increase the lattice ratio c/a , an increase in tendency for basal slip can occur. A reduction in adhesion can be anticipated with basal slip (ref. 5).

In table I the adhesion characteristic for titanium is high. This high value is believed to be due, as mentioned earlier, to the mode of slip behavior for titanium. Because a number of prismatic and pyramidal planes exist, a greater tendency for plastic deformation can take place for metals, such as titanium, than for basal-slip hexagonal metals, such as beryllium and cobalt. Titanium, therefore, under deformation behaves more like the cubic metals (copper, table I). With a greater ease of plastic deformation under an applied stress, a greater real area of metal-to-metal contact can occur. With the titanium-aluminum alloys, the expansion of the lattice increases the tendency for basal slip and thereby reduces the ease of plastic deformation, contact area, and adhesion. With simple basal slip, adhesion should be at a minimum.

[SUMMARY OF RESULTS]

The following results were obtained from an investigation of the friction, wear, and adhesion characteristics of titanium-aluminum alloys in vacuum:

1. The addition of aluminum to titanium reduced the friction, adhesion, and wear of titanium appreciably in vacuum because of an expansion of the c/a lattice ratio of the hexagonal unit cell of titanium.

2. A titanium - 21-weight-percent-aluminum alloy sliding on itself and on 440-C stainless steel exhibited lower friction and wear characteristics in vacuum than did the two standard bearing steels 52100 and 440-C.

3. Lower friction characteristics and higher rider wear were found for titanium-aluminum alloys sliding on 440-C stainless steel than when they were sliding on themselves.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 26, 1965.

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TABLE I. - ADHESION OF VARIOUS MATERIALS IN VACUUM

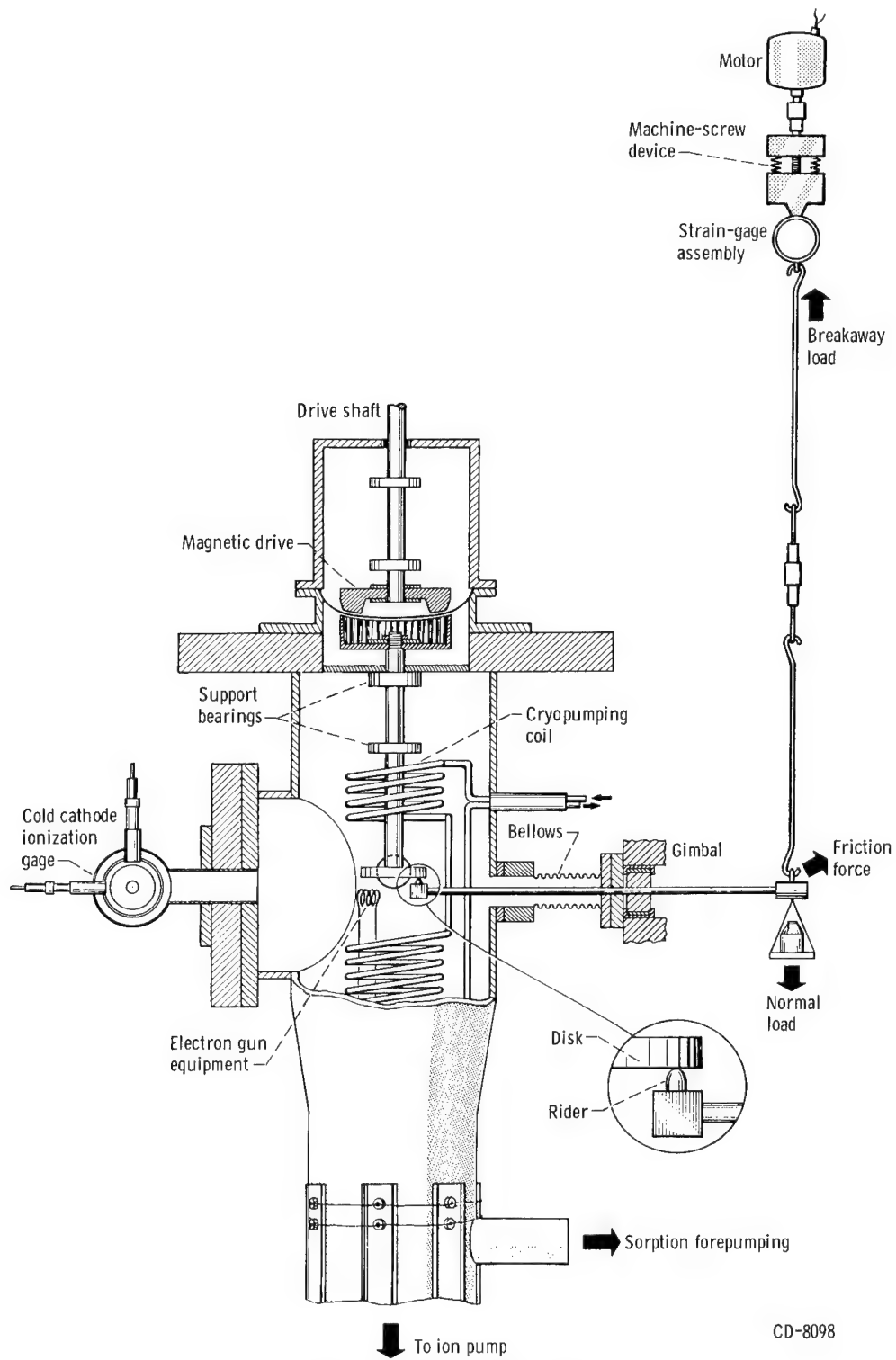
[Normal applied load, 1000 g; rider, 3/16-in.-rad.
hemisphere; flat disk; pressure, 10^{-9} mm Hg.]

Material combination	Breakaway load, g	Adhesion coefficient	Conditions
Cu/Cu	400	0.4	Simple contact; normal surface oxides present
Cu/Cu	3800	3.8	Simple contact; surfaces cleansed at 400 ⁰ C to dissociate surface oxides
Cu/Cu	4200	4.2	Rotation of specimen for 1.5 min at 197 cm/sec ^a
Ti/Ti	5300	5.3	Rotation of specimens for 30 min at 197 cm/sec ^a
Ti-11Al/Ti-11Al	(b)	<.05	Rotation of specimen for 60 min at 197 cm/sec ^a
Ti-16Al/Ti-16Al	(c)	<.05	Rotation of specimen for 60 min at 197 cm/sec ^a
Ti-21Al/Ti-21Al	(c)	<.05	Rotation of specimen for 60 min at 197 cm/sec ^a

^aRotation of specimens in contact to disrupt any residual surface oxides and where possible induce work hardening.

^bToo low to measure.

^cSpecimens not adhered together after run.



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Figure 1. - Vacuum friction apparatus.

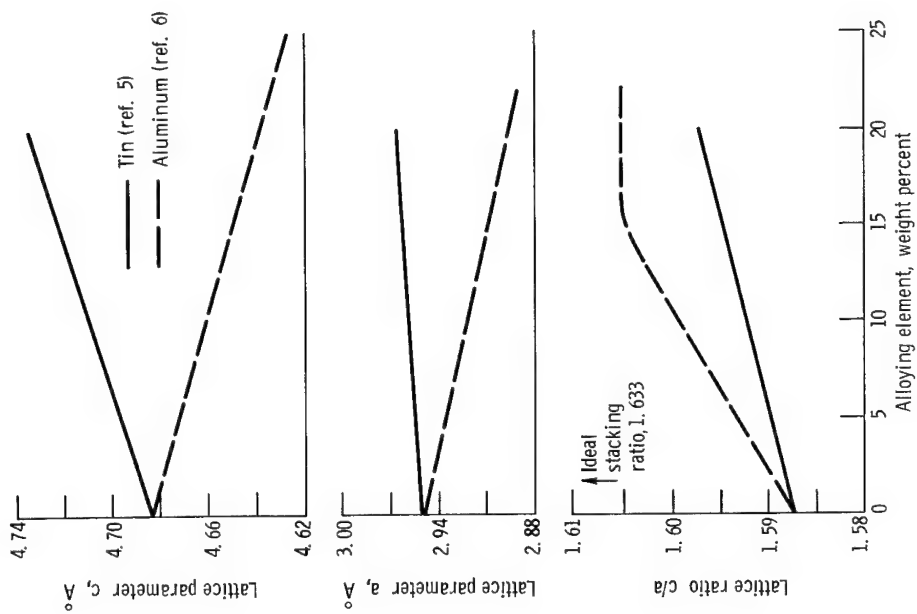


Figure 2. - Effect of alloying elements tin and aluminum on crystal lattice parameters of titanium (refs. 5 and 6).



(a) Cast titanium (no aluminum).



(b) Titanium - 21-weight-percent-aluminum.

Figure 3. - Photomicrographs of unalloyed titanium and titanium - 21-weight-percent-aluminum alloy. X50. (Reduced 50 percent in printing.)

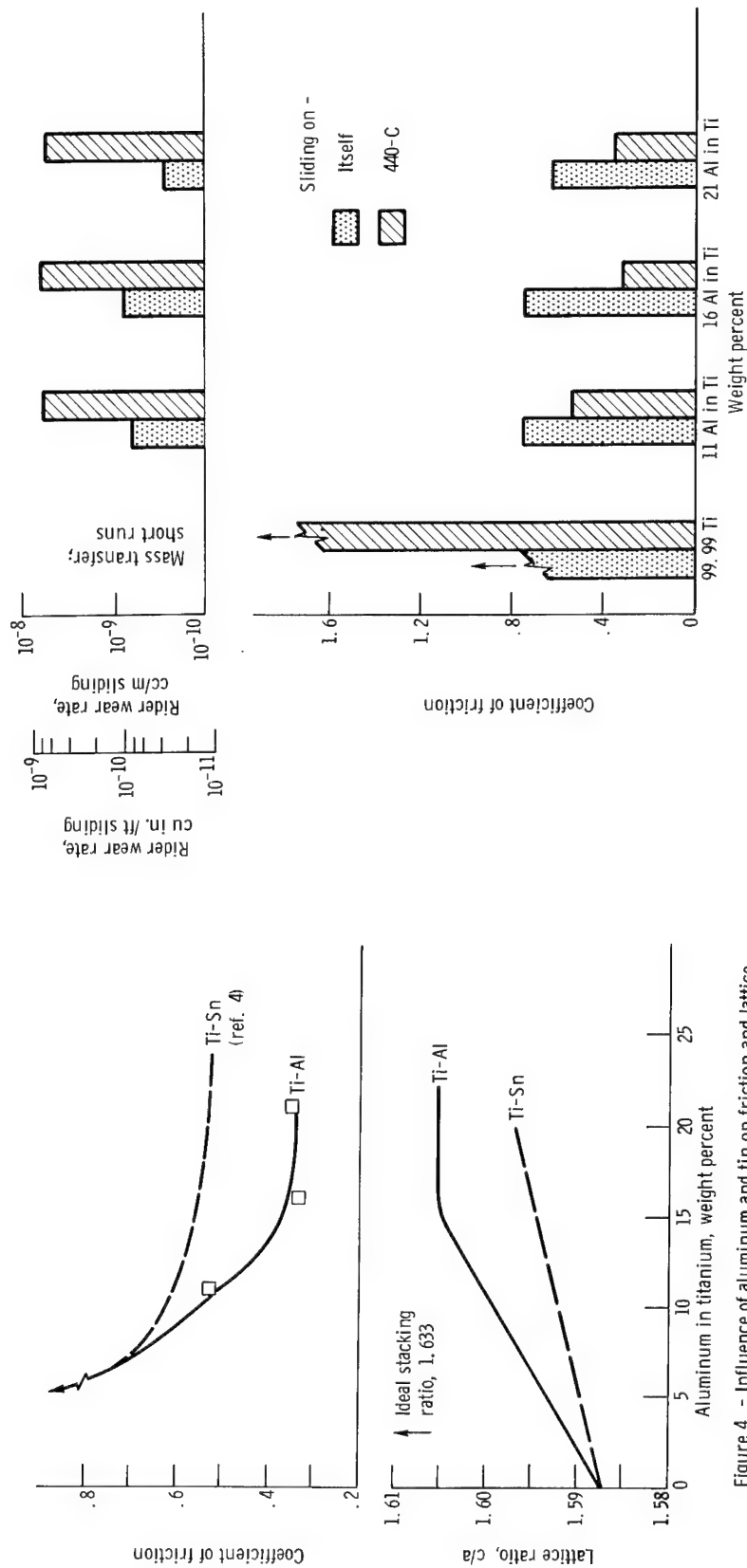
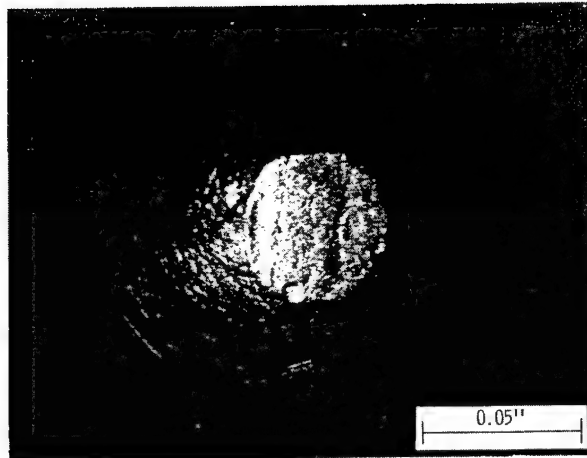
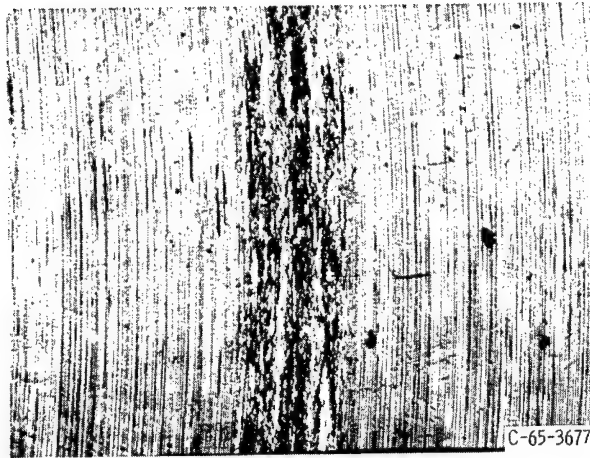


Figure 4. - Influence of aluminum and tin on friction and lattice ratio characteristics for titanium sliding on 440-C stainless steel in vacuum (10⁻⁹ mm Hg). Load, 1000 grams; sliding velocity, 197 centimeters per second; no external heating.

Figure 5. - Coefficient of friction and rider wear for titanium and titanium-aluminum alloys sliding on themselves and on 440-C stainless steel in vacuum (10⁻⁹ mm Hg). Load, 1000 grams; sliding velocity, 197 centimeters per second; duration of run, 1 hour; no external heating.



(a) Rider wear area.



(b) Disk wear track.



(c) Surface profile trace.

Figure 6. - Photomicrographs of rider and disk and profile trace of disk surface of titanium - 21-weight-percent-aluminum alloy sliding on itself in vacuum (10^{-9} mm Hg). Load, 1000 grams; sliding velocity, 197 centimeters per second; duration of run, 1 hour; no external heating.

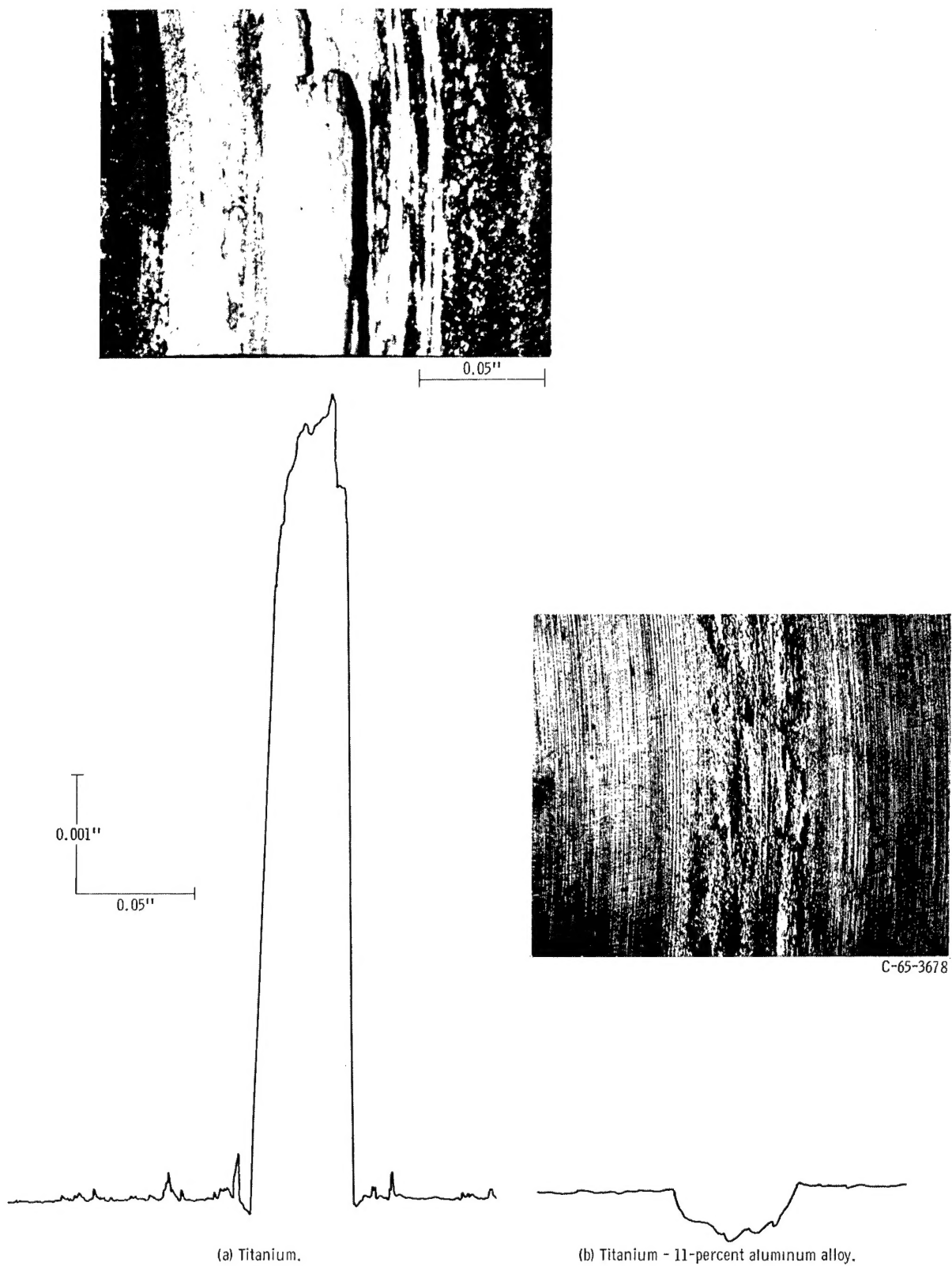


Figure 7. - Photomicrographs and surface profile traces of wear areas made by titanium and titanium - 11-weight-percent-aluminum sliding on titanium and on titanium - 11-weight-percent-aluminum, respectively, in vacuum (10^{-9} mm Hg).

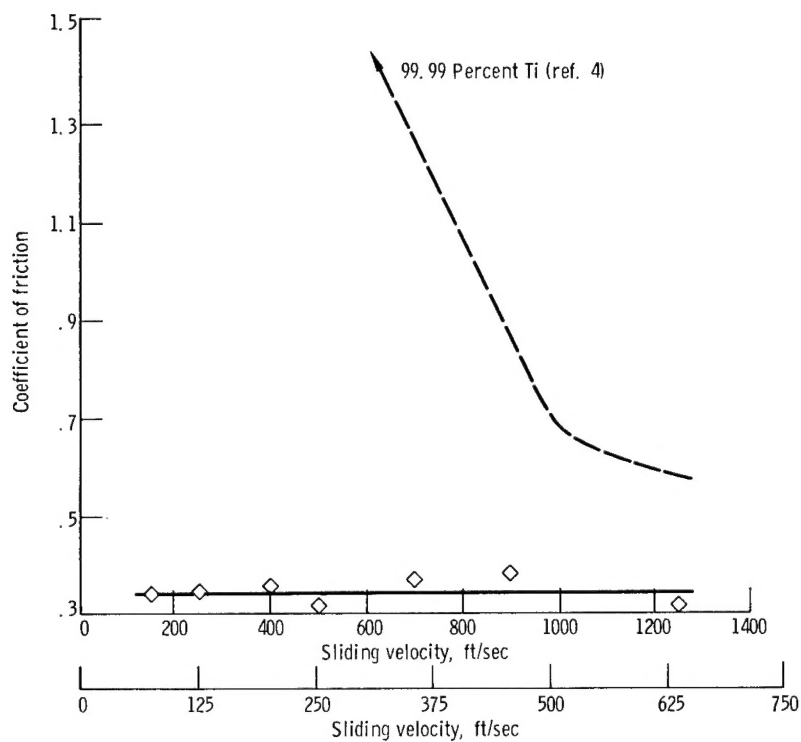


Figure 8. - Influence of 21 weight percent aluminum on friction coefficient of titanium sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg) at various sliding velocities. Load, 1000 grams; no external heating.

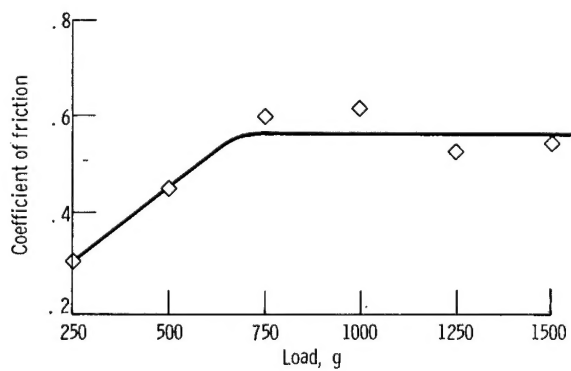


Figure 9. - Coefficient of friction as a function of normal load for titanium - 21-percent-aluminum alloy sliding on itself in vacuum (10^{-9} mm Hg). Sliding velocity, 197 centimeters per second; ambient temperature, 25° C.

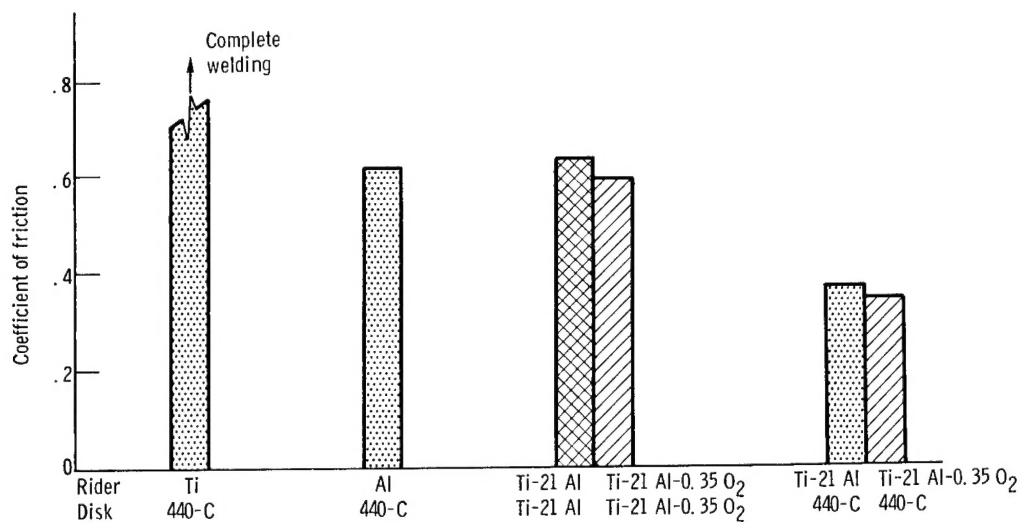


Figure 10. - Influence of alloying elements on friction coefficient of titanium in vacuum (10^{-9} mm Hg). Load, 1000 grams; sliding velocity, 197 centimeters per second; no external heating.

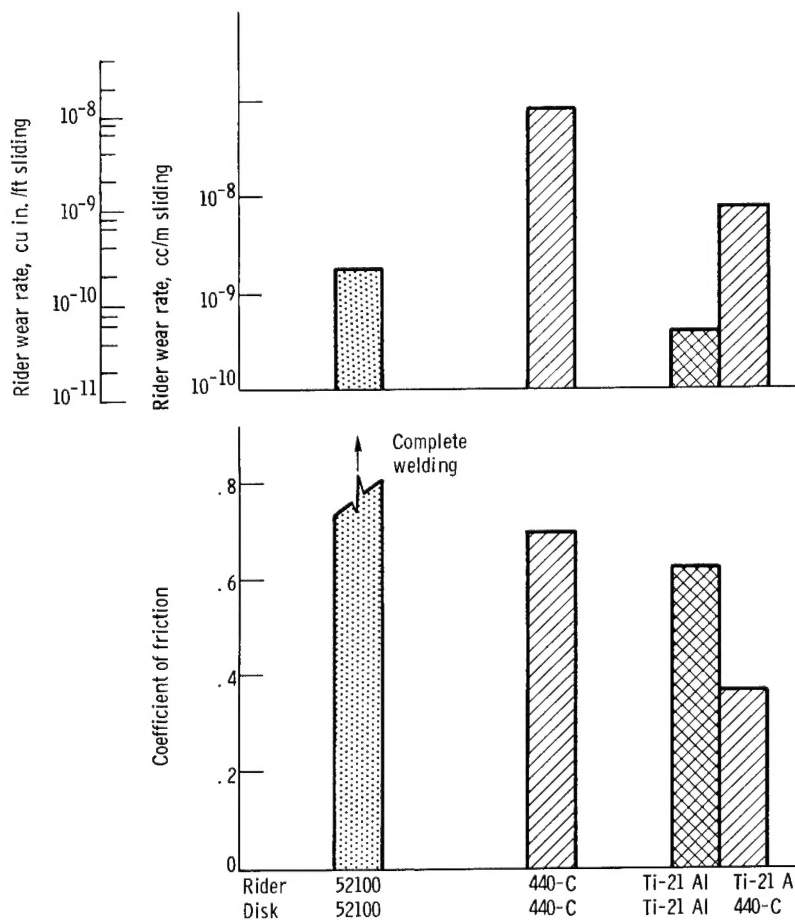


Figure 11. - Coefficient of friction and rider wear for various alloys in vacuum (10^{-9} mm Hg). Load, 1000 grams; sliding velocity, 197 centimeters per second; duration of run, 1 hour; no external heating. (Data for 52100 sliding on 52100 from ref. 4).

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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